available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/biocon

Forest fragmentation and edge effects from deforestation and selective logging in the Brazilian Amazon

Eben N. Broadbent[a,b,*], *Gregory P. Asner*[a], *Michael Keller*[c], *David E. Knapp*[a], *Paulo J.C. Oliveira*[a], *Jose N. Silva*[d]

[a]*Department of Global Ecology, Carnegie Institution, Stanford, CA 94305-4101, USA*
[b]*Department of Biological Sciences, Stanford University, Stanford, CA 94305-4101, USA*
[c]*USDA Forest Service, International Institute of Tropical Forestry, Rio Piedras, PR USA and Complex Systems Research Center, Morse Hall, University of New Hampshire, Durham, NH 03824-3518, USA*
[d]*EMBRAPA-Amazonia Oriental, Trv. Dr Eneas Pinheiro SN, Belem CEP 66095-100, Pará, Brazil*

ARTICLE INFO

Article history:
Received 18 November 2007
Received in revised form
23 March 2008
Accepted 8 April 2008
Available online 17 June 2008

Keywords:
Forest core
Forest texture
Landscape ecology
Rainforest
Remote sensing
Sustainability

ABSTRACT

Forest fragmentation results from deforestation and disturbance, with subsequent edge effects extending deep into remaining forest areas. No study has quantified the effects of both deforestation and selective logging, separately and combined, on forest fragmentation and edge effects over large regions. The main objectives of this study were to: (1) quantify the rates and extent of forest fragmentation from deforestation and logging within the Brazilian Amazon, and (2) contextualize the spatio-temporal dynamics of this forest fragmentation through a literature review of potential ecological repercussions of edge creation. Using GIS and remote sensing, we quantified forest fragmentation – defined as both increases in the forest edge-to-area ratio and number of forest fragments – and edge-effected forest occurring from these activities across more than 1.1 million km^2 of the Brazilian Amazon from 1999 to 2002. Annually, deforestation and logging generated ~32,000 and 38,000 km of new forest edge while increasing the edge-to-area ratio of remaining forest by 0.14 and 0.15, respectively. Combined deforestation and logging increased the edge-to-area ratio of remaining forest by 65% over our study period, while generating 5539 and 3383 new forest fragments, respectively. Although we found that 90% of individual forest fragments were smaller than 4 km^2, we also found that 50% of the remaining intact forests were located in contiguous forest areas greater than 35,000 km^2. We then conducted a literature review documenting 146 edge effects and found that these penetrated to a median distance of 100 m, a distance encompassing 6.4% of all remaining forests in our study region in the year 2002, while 53% of forests were located within two km of an edge. Annually deforestation and logging increased the proportion of edge-forest by 0.8% and 3.1%, respectively. As a result of both activities, the total proportion of edge-forest increased by 2.6% per year, while the proportion within 100-m increased by 0.5%. Over our study period, deforestation resulted in an additional ~3000 km^2 of edge-forest, whereas logging generated ~20,000 km^2, as it extended deep into intact forest areas. These results show the large extent and rapid expansion of

* *Corresponding author:* Address: Department of Global Ecology, Carnegie Institution, Stanford, CA 94305-4101, USA. Tel.: +1 650 704 2065; fax: +1 650 462 5968.
E-mail addresses: eben@stanford.edu (E.N. Broadbent), gpa@stanford.edu (G.P. Asner), michael@kaos.sr.unh.edu (M. Keller), dknapp@globalecology.stanford.edu (D.E. Knapp), poliveira@globalecology.stanford.edu (P.J.C. Oliveira), natalino@cpatu.embrapa.br (J.N. Silva).

doi:10.1016/j.biocon.2008.04.024

previously unquantified soft-edges throughout the Amazon and highlight the need for greater research into their ecological impacts.

1. Introduction

Forest fragmentation and edge effects from deforestation have been identified as one of the most pervasive and deleterious processes occurring in the tropics today (Gascon et al., 2000; Murcia, 1995; Skole and Tucker, 1993). Forest fragmentation results from the simultaneous reduction of forest area, increase in forest edge, and the sub-division of large forest areas into smaller non-contiguous fragments (Laurance, 2000). The detrimental effects of forest fragmentation from deforestation include increases in wildfire susceptibility (Alencar et al., 2004; Cochrane and Laurance, 2002; Cochrane et al., 2002) and tree mortality, changes in plant and animal species composition (Tabanez and Viana, 2000; Barlow et al., 2006; Cushman, 2006), and seed dispersion (Rodríguez-Cabal et al., 2007; Cramer et al., 2007) and predation (Herrerías-Diego et al., 2008) and easier access to interior forest, leading to increased hunting and resource extraction (Peres, 2001) or conversion to agroscape (Kaimowitz and Angelsen, 1998).

Forest fragmentation results in an increased proportion of the remaining forest being located in close proximity to the forest edge (Saunders et al., 1991). Detrimental edge effects extend into interior forest areas from these transition zones. While the majority of these effects are thought to extend no further than 1 km (Murcia, 1995), some may extend as far as 5–10 km into intact forest areas (Curran et al., 1999). The negative impacts of edge effects on ecosystems include shifts in plant and animal community composition and changes in diversity (Benitez-Malvido and Martinez-Ramos, 2003; Cagnolo et al., 2006), increased rates of tree mortality (Nascimento and Laurance, 2004), and fire susceptibility (Cochrane and Laurance, 2002), altered microclimates (Williams-Linera et al., 1998), and increased carbon emissions (Laurance et al., 1997, Laurance and Williamson, 2001), primarily from increased mortality of large trees (Laurance et al., 2000).

Although research employing remote sensing and GIS have quantified significant fragmentation and potentially edge-effected forest from deforestation at small scales, few have been at the scale representative of the Amazon region. Large-scale impacts at the Amazon were highlighted by Skole and Tucker (1993) who showed that, in 1988, ~16,000 km^2 of remaining forest occurred within ~10,000 forest fragments <100 km^2, while the remaining 3,600,000 km^2 of intact forest occurred in a similar number of fragments. They calculated that potentially edge-effected forest (up to 1 km into interior forest) within these fragments affected an area 68% larger than that of the deforested area alone. Similar results from deforestation have been found at smaller scales. Forest subdivision was documented by Ranta et al. (1998) in 629 km^2 of the Brazilian Atlantic coastal region where the majority of forest fragments were found to be smaller than 30 ha, and by Cochrane (2001) for 1280 km^2 in northeastern Pará where the majority of the remaining forests were located within a few large contiguous forest areas and that over 50% and ~85% of the remaining forest was within 300 m and 1 km, respectively, of a forest edge. Cochrane et al. (2002) later studied 16,819 km^2 in the Sinop region of Mato Grosso, Brazil, and calculated that 52% of the remaining 12,271 km^2 of forests were within one km of the nearest edge.

In this study we present selective logging as a previously unquantified driver of rapid and extensive forest fragmentation and subsequent edge effects in the Brazilian Amazon. Selective logging, which has only recently been mapped across the Brazilian Amazon, annually impacts as much forest area as the area converted to pasture or agriculture (Asner et al., 2005). In the Brazilian Amazon, only 2–9 merchantable species are removed per hectare of forest logged, but this process results in considerable ground and canopy damage (Asner et al., 2006; Pereira et al., 2002). Although the forest-to-logged forest transition is less abrupt than that between forest and pasture or agricultural areas, the effects of logging on forest ecological, hydrological, and microclimatic processes have been well documented (Uhl et al., 1991; Veríssimo et al., 1992). Selective logging has been shown to cause alterations in forest biophysical properties, including water and wind stress, and changes in micrometeorological and aquatic systems (Pringle and Benstead, 2001), which may lead to an increased vulnerability to fires (Cochrane, 2001; Nepstad et al., 1999), as well as changes in overall forest structure and composition (Nepstad et al., 1992). Selective logging also has a direct impact on faunal populations, including insects (Lawton et al., 1998), primates (Johns and Johns, 1995), birds (Mason and Thiolay, 2001), bats (Soriano and Ochoa, 2001), and arboreal animals in general (Putz et al., 2001a,b). Like fragmentation, logging also leads to increased human access and reductions in animal populations and forest resources through hunting and extraction (Nepstad et al., 1992).

Although selective logging has been described as an integral large-scale driver of forest fragmentation (Gascon et al., 2000; Laurance, 2000), and Asner et al. (2006) have shown that timber extraction is occurring over large areas at high intensities, no study has yet quantified the extent and rate of forest fragmentation and edge effects from both deforestation and selective logging at large scales. The main objectives of this study were to: (1) quantify the rates and extent of forest fragmentation within the Brazilian Amazon, with an emphasis on comparing soft- and hard-edges, and (2) contextualize the spatio-temporal dynamics of this forest fragmentation through a literature review of potential ecological repercussions of edge creation. To address these objectives we present new data highlighting the intensity, longevity and fine-scale spatial distribution of canopy damage following selective logging, then we quantify the large-scale extent and annual rates of forest fragmentation – defined as both increases in the forest edge-to-area ratio and number of forest fragments – from deforestation (referred to as *hard-edges*) and selective logging (referred to as *soft-edges*) from 1999 to 2002 across 1.12 million km^2 of the Brazilian Amazon "arc of deforestation". We then conduct an extensive literature review to document the variety and intensity of measured edge effects, and to quantify the total area and annual change in the area of forest potentially degraded by edge effects extending from deforested and selectively logged areas.

2. Materials and methods

2.1. Study region

The study region covered portions of four states (Acre, Mato Grosso, Pará, and Rondônia) in the Brazilian Amazon region which had deforestation and logging coverage over the study period 1999–2002. Areas with atmospheric interference (clouds or other) during any study year were removed from the analysis. The final study area encompassed over 1.12 million km^2. The selected area encompassed >80% of the deforestation (INPE, 2005) and selective logging (Asner et al., 2005) occurring within the Brazilian Amazon (Fig. 1). Although the majority of cloud interference problems were encountered in northern Pará, only a small section of northeastern Pará included significant incidence of logging or deforestation. Contiguous forested fragments smaller than 0.05 km^2 were excluded from our analysis as they frequently resulted from spatial misregistration errors.

2.2. Deforestation and logging maps

Maps of logging were obtained from the Carnegie Landsat Analysis System (CLAS), a system developed to identify forest disturbances and selective logging over large areas. A detailed description of the CLAS methodology, including the uncertainty analysis and validation effort, was provided in Asner et al. (2005). The final CLAS output is a map of logged areas within which canopy damage is quantified in each pixel, with a reported error of 11–14% (see Fig. 2).

Maps of deforestation were obtained from the *Program for Monitoring Deforestation in the Brazilian Amazon* (PRODES) of the Brazilian Institute for Space Research (INPE). PRODES deforestation maps in Geographic Information System (GIS) format are freely available at http://www.obt.inpe.br/prodes/ , and are considered to be the best deforestation maps available for the Brazilian Amazon (Defries et al., 2005). The PRODES data used in this paper were accessed from September 2005 to May 2006. These data are subject to a 4% error from atmospheric conditions, spatial misregistration, or misclassification (INPE, 2005). PRODES began producing spatially accurate maps of annual deforestation in 2000–2001, whereas the year 2000 PRODES map represents cumulative deforestation from 1997 to 2000. In order to compare 1999–2000 CLAS logging to one year of PRODES deforestation, we calculated the mean annual change from the 1997 to 2000 PRODES data.

Both the deforestation and logging maps are based on 30-m resolution Landsat Enhanced Thematic Mapper Plus (ETM+)

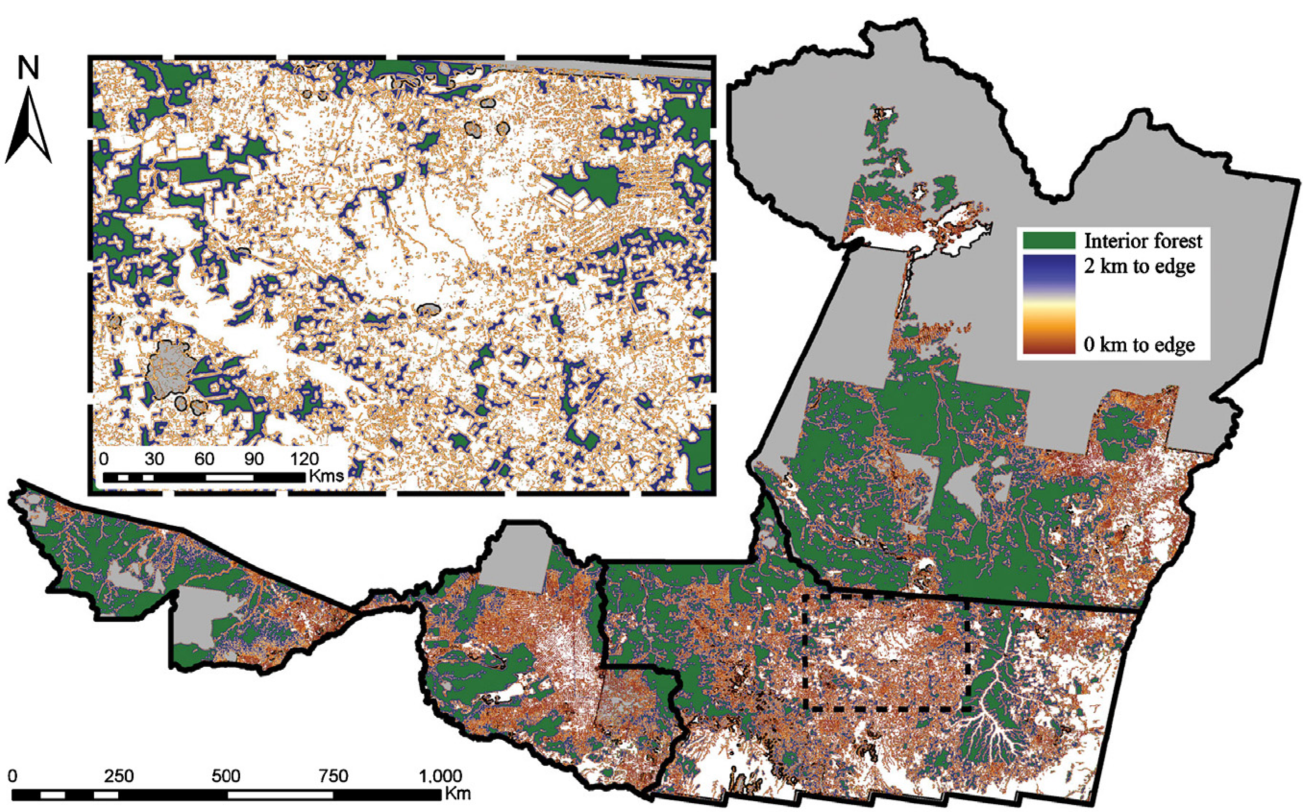

Fig. 1 – Interior and edge-forest (⩽2 km edge) within our study area following deforestation and cumulative logging (2000–2002). White areas represent non-forest areas (i.e., pasture or agriculture) within our study area while grey areas represent those areas not included due to cloud interference or missing imagery.

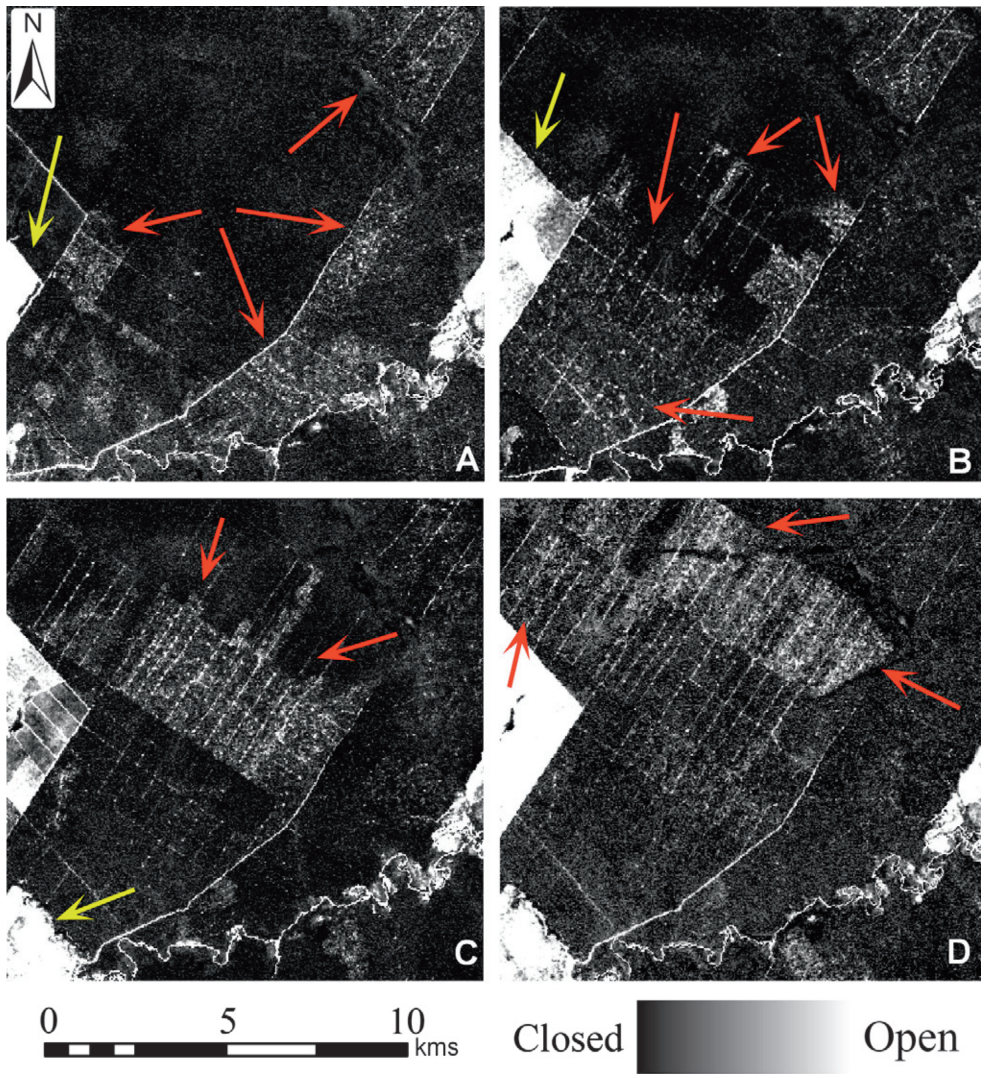

Fig. 2 – Example of spatio-temporal dynamics of deforestation and selective logging in the years 1999–2002 (A–D, respectively) in central Mato Grosso. Areas of deforestation and new logging are indicated by yellow and red arrows, respectively. Subdivided forest fragments are visible within logged areas.

satellite imagery. The minimum deforested or logged area identified by the PRODES deforestation and CLAS logging was approximately 6 ha. We integrated the deforestation and logging maps in a GIS to quantify the impacts of deforestation with both new and up to three years of cumulative logging. We define *new logging* as logging occurring in the study year and *cumulative logging* as that occurring over multiple years. We quantified separately the fragmentation and edge effects of deforestation, new logging, and cumulative logging. As forest edge occurred simultaneously proximate to deforested and logged areas we defined logging edge length and edge-forest extent as that which occurred in addition to that caused by deforestation through the specified study year.

2.3. *Forest fragmentation and structure*

We quantified forest structure at a fine-scale within logged areas and forest fragmentation at a large-scale for all forests within our study area. The effect of logging on fine-scale forest structure was investigated using canopy texture, which we define as the mean absolute difference in forest gap fraction between adjacent pixels, within a moving 6×6 pixel window. Forest canopy-gap fraction (e.g., canopy openness *sensu* Pereira et al., 2002) is an indicator of forest structure that affects leaf physiology, forest carbon budgets, water balances, primary production, microclimate, and biodiversity (Brokaw, 1982; Mulkey and Pearcy, 1992). In this study, we used remotely sensed canopy-gap fraction images developed through extensive field work and described in detail by Asner et al. (2006). Canopy texture was used to quantify differences in the spatial distribution and extent of canopy damage between logged areas and intact forest. We used one-way ANOVA with Tukey's HSD post hoc test to evaluate significance of gap fraction and texture for up to two years post-logging. We randomly choose 25% of the available samples (n = 330,433) to limit the effects of spatial autocorrelation in our statistical comparison.

At the large-scale, we used two metrics of forest fragmentation: (1) the edge-to-area ratio (fragment edge/area) of all forest within our study area, hereafter referred to as *edge-to-area fragmentation*, and (2) the overall number of non-contiguous forest fragments, hereafter referred to as *subdivision fragmentation*. Changes in fragmentation were identified following 2000–2002 deforestation alone, and after including the additional impacts of new and cumulative logging. We quantified total edge length occurring from both deforestation and logging as well as natural sources (including transitions from forest to river or natural non-forested areas) and used temporal changes to discern anthropogenic impacts. The forest interface used in the calculations depended on the deforestation-logging combination because logging and the different ages of logged areas were either ignored or included as a source of additional forest edge interface over that of deforestation. We describe these combinations using a "D" for deforestation and an "L" for logging, followed by the included year (s). As the impact of a logged area would change with time post-harvest, we created combinations including and excluding older years of logging. These combinations were not necessary for deforestation, as we did not consider regeneration of deforested areas during our study period, although we recognize that soft- and hard-edge structure and influence changes with time (Didham and Lawton, 1999). The number of individual forested fragments, as well as their edge length and area, were calculated over the study area for the years 1997 and 2002. A maximum area threshold of 350 km^2, which included 99.5% of all forest fragments, was used to exclude the very largest forest areas which were contiguous between study states.

2.4. *Forest edge effects*

We limited our analysis to forested areas within two km of the nearest forest edge – hereafter referred to as *edge-forests* – based on the results of our spatial analysis and literature review, both of which showed that two km encompassed nearly all documented edge effects and potentially affected forest area in our study region (Fig. 3). Linear distance maps to the nearest forest edge were created for all deforestation–logging combinations at a spatial resolution of 100 × 100 m, the maximum possible considering computing requirements.

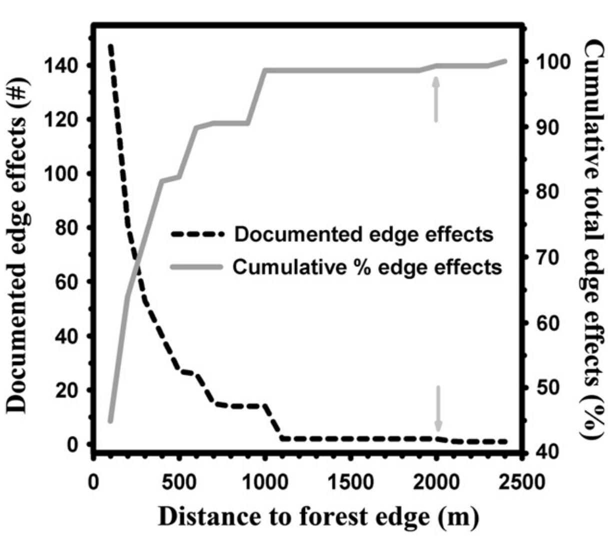

Fig. 3 – Total number (left) and cumulative percentage (right) of edge effects documented in our literature review. References are provided in Appendix A.

2.5. *Literature review*

We performed a literature review using academic search engines from December, 2005 to February, 2006 for the terms "forest fragmentation" and "edge effects" in peer-reviewed articles. We then iteratively scanned the bibliographies of the articles until no new relevant articles were identified. We recorded specific edge effects and the distance to which these effects penetrated the forest interior. All documented edge effects, including both temperate and tropical regions, were included in our review. We divided the reported impacts into four broad categories: (1) forest structure, (2) tree mortality, (3) forest microclimate, and (4) biodiversity.

3. Results

3.1. *Forest fragmentation*

At the fine-scale logging immediately increased the mean forest gap fraction from 14% to 22%, while doubling the mean canopy texture from 7% to 13% ($p < 0.05$; ANOVA). Changes in canopy-gap fraction and texture remained significant during the two years following harvest (Tukey's HSD; $p < 0.05$). The largest decreases in canopy-gap fraction and texture occurred in the year immediately following logging, with the means decreasing from 13% and 22% to 8% and 15%, respectively. An example of the spatio-temporal dynamics of deforestation and logging is provided in Fig. 2.

Results from the large-scale analyses of edge-to-area and subdivision fragmentation are provided in Table 1 and Fig. 4. During our study period, forest area decreased 13% from deforestation and cumulative logging, while edge length increased 69%, resulting in an increase in edge-to-area fragmentation of 61%. Annually new logging directly impacted about the same area as deforestation, while creating 117% more new forest edge. Subdivision from these activities increased the total number of forest fragments 74%, from 15,229 to 26,516 (Table 1). Annually new logging increased the number of forest fragments by 39%; however, when considered cumulatively (2000–2002), logging resulted in a 64% increase in total forest fragments. Although around 90% of individual forest fragments were smaller than 4 km^2 (Fig. 4A), more than 50% of total remaining forest occurred in fragments greater than 35,000 km^2 (Fig. 4B).

In addition to large-scale subdivision fragmentation, individual forest fragments themselves became increasingly edge-to-area fragmented. Between 1997 and 2002, including deforestation only, the mean (std. dev.) area and perimeter of individual forest fragments decreased significantly from 3.5 (15.9) to 2.6 (13.7) km^2 and from 10.3 (28.4) to 9.8 (27.9) km, respectively, while the mean edge-to-area ratio increased from 9.3 (5.3) to 14.6 (11.3) (Tukey's HSD; $p < 0.05$). The addition of cumulative logging (2000–2002) did not significantly increase the edge-to-area fragmentation of these fragments over that of deforestation alone.

Table 1 – Fragmentation statistics for all deforestation and logging combinations within our study region

Deforestation year (⩽)[a]	Logging year (s)[b]	ID	Forest area (km^2)	Edge length (km)	Edge-to-area ratio	Forest area ⩽ 2 km edge (km^2)	Forest area ⩽ 2 km edge (%)	Forest fragments (#)
1997	–		791 418	427 001	0.54	348 504	44.0%	15 229
2000	–	D0	758 474	455 954	0.60	345 563	45.6%	17 594
2001	–	D01	747 379	500 433	0.67	357 985	47.9%	19 699
2002	–	D012	733 626	543 638	0.74	348 589	47.5%	23 133
2000	2000	D0 L0	743 789	494 579	0.66	369 024	49.6%	18 631
2001	2001	D01 L1	733 772	542 186	0.74	369 678	50.4%	20 463
2002	2002	D012 L2	722 115	576 625	0.80	363 116	50.3%	23 773
2001	2000–2001	D01 L01	721 590	566 377	0.78	350 556	48.6%	21 863
2002	2001–02	D012 L12	710 628	605 112	0.85	370 503	52.1%	24 943
2002	2000–2002	D012 L012	699 855	621 713	0.89	368 150	52.6%	26 516
Annual change								
New logging (Avg. 2000–2002)			−13 268	37 788	0.06	16 560	3.1%	814
Deforestation (Avg. 2000–2002)			−11 943	32 445	0.05	682	0.8%	2109
Cumulative change[c]								
Deforestation (2000–2002)			−24 848	87 684	0.14	3026	1.9%	5539
Logging (2000–2002)			−33 771	78 075	0.15	19 561	5.1%	3383

a Deforestation is always cumulative through study year.
b Signifies that logging is not included in the spatial analysis.
c Logging impacts are in addition to deforestation.

3.2. *Forest edge effects*

Results of the forest edge analysis are provided in Table 1 and Figs. 4 and 5. By the year 2002, including deforestation only, the proportion of edge-forests in the study region had increased to 48%. Cumulative logging (2000–2002) further increased the proportion of edge-forest to 53% (Table 1), with 37% of remaining forest being within 1 km and 6.4% being within 100 m of the nearest edge (Fig. 4C), while more than 50% of all edge-forest occurred within 0.6 km of the nearest edge (Fig. 4D). The explicit spatial dynamics of edge-forest generation from deforestation, and new and cumulative logging are illustrated in Fig. 5. Annually, the total percentage of remaining forests less than two km from an edge increased by 2.6%, while the proportion within 100-m increased by 0.5% (Fig. 5). Deforestation increased the area of forest up to ~0.5 km, but decreased forest area from 0.5 to 2 km into interior forest, while new logging increased the forest area <1.8 km into intact forest areas, and then decreased the forest area up to 2 km study limit. Deforestation annually increased the area of forest within 100 m of the forest edge by 1800 km^2, while the addition of new and cumulative logging increased the forest area by 2500 and 4800 km^2, respectively (Fig. 5).

3.3. *Literature review*

The effects of edges on tropical and temperate forest attributes and function were abundantly documented in the literature (Figs. 3 and 6). Although our literature review initially identified hundreds of articles, only 62 of these provided explicit interior forest penetration distances for edge effects. Approximately 45% of all documented edge impacts extended ⩽100 m, while 99% of documented edge impacts extended ⩽ 2 km, into the surrounding forest. The 146 reported edge effects were divided about equally among four categories: (A) forest structure, (B) tree mortality, (C) microclimate, and (D) biodiversity (Fig. 6). Descriptive statistics for these categories are provided in Table 2, and complete references are provided in Appendix A.

Our review documented numerous impacts of hard-edges. In general, immediately following conversion of intact forest to pasture or agriculture, microclimatic alterations occur in the nearby surrounding forest edges through increased penetration of sunlight and wind (Didham and Lawton, 1999). Air and soil moisture decrease (Williams-Linera et al., 1998), while there are increases in temperature (Cadenasso et al., 1997), vapor pressure deficit (Davies-Colley et al., 2000) and the availability of photosynthetically active radiation to the understory (Kapos, 1989), and throughout the forest edge (Young and Mitchell, 1994). Litterfall production increases (Sizer et al., 2000), as does the accumulated depth of the litter layer (Matlack, 1993), resulting in rapid increases in susceptibility to wildfire (Cochrane and Laurance, 2002), especially as forest edges are often located adjacent to agricultural or pasture lands that are often burned as part of their management (Peres, 2001).

Following edge creation, forest structure and composition can be altered both in interior forest (Mesquita et al., 1999) or at the forest edge (Didham and Lawton, 1999), as large trees often die off within 300 m of the forest edge (Laurance et al., 2000), being replaced by densely spaced short-lived pioneers (Laurance et al., 2006), resulting in decreases in forest biomass (Nascimento and Laurance, 2004) and basal area (Harper et al., 2005). Tree mortality is also linked to positive feedbacks with fires (Cochrane, 2001), resulting in further loss of biomass (Laurance and Williamson, 2001) and carbon emissions to the atmosphere through increased turnover of necromass (Nascimento and Laurance, 2004). The change to a smaller statured

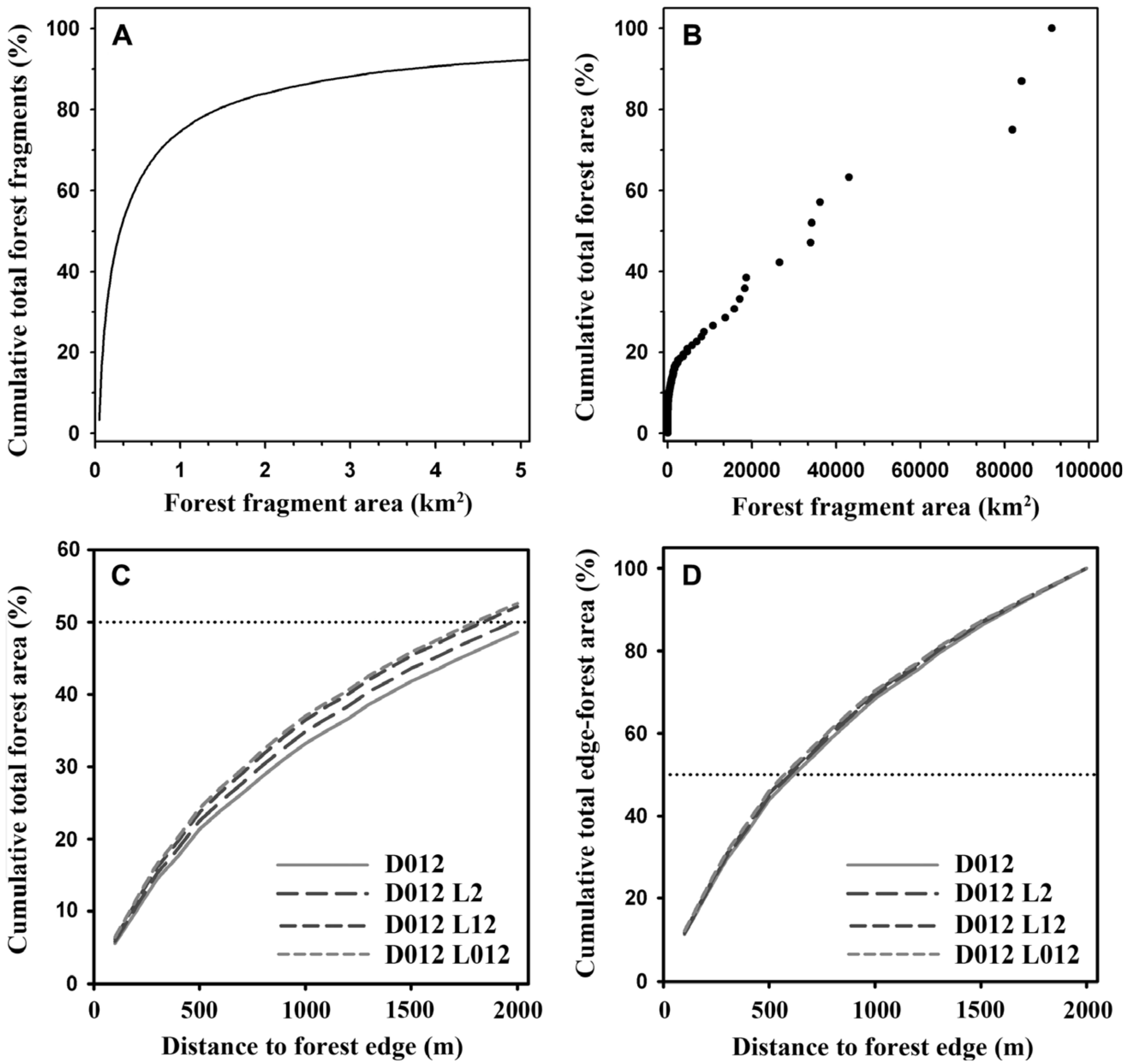

Fig. 4 – Cumulative percentage of (A) total non-contiguous forest fragments in our study region versus each fragment's area (km^2), (B) total forested area in our study region versus the area of individual non-contiguous forest fragments, (C) cumulative total forested area (km^2), and (D) total remaining forest, located within individual 100 m distance increments up to two km from the nearest forest edge. Logging impacts are in addition to those caused by deforestation.

forest (Didham and Lawton, 1999), sometimes containing more chemical defenses (Hester and Hobbs, 1992), occurs through loss of native vegetation and often leads to an increased abundance of invasive species (Hobbs, 2001). Changes in structure and composition, accompanied by disruptions in plant–animal interactions (Rodríguez-Cabal et al., 2007), in turn, often lead to invasion of disturbance-adapted animal species, including butterflies (Lovejoy et al., 1986), beetles (Didham, 1997; Nichols et al., 2007), pigs (Peters, 2000), birds (Hagan et al., 1996), frogs and lizards (Schlaepfer and Gavin, 2001), and mammals (Kinnaird et al., 2003), while insect biomass moves from the overstory to the understory (Malcolm, 1997).

Only four of the 62 reviewed articles addressed soft-edges. Pereira et al. (2002) and Asner et al. (2004) found that tree-felling gaps caused significant increases in canopy openness for up to 100 m in the surrounding forest. Uhl and Buschbacher (1985) and Cochrane et al. (2004) highlighted the positive synergism between anthropogenic fires and wildfires in selectively logged forests. Given the paucity of literature on the ecological impacts of soft-edges and the very large length and area they occupy there is a clear need for additional studies of soft-edge impacts on biodiversity and ecosystem function.

4. Discussion

Although deforestation has been measured for decades, the full extent and spatial distribution of selective logging in the

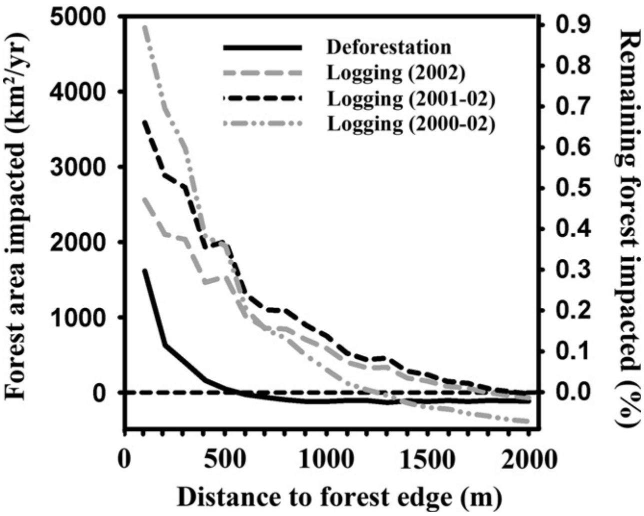

Fig. 5 – Mean annual change in edge-forest area and the percentage of total remaining forest impacted within individual 100 m distance increments up to two km into the forest interior. New logging and cumulative logging (2000–2002) impacts are in addition to those of deforestation.

Amazon has only recently been mapped. Asner et al. (2005) showed the logging annually impacts a forest area equal in size (~12,000–19,000 km^2 annually) to that deforested. Subsequent analysis revealed that ⩾76% of selective logging resulted in high levels of forest canopy damage, and that much of the area selectively logged was deforested within several years (Asner et al., 2006). Preliminary analysis of the selective logging data showed substantially different patterns in spatial distribution between selective logging and deforestation, which prompted the full spatial analysis presented in this study.

Traditionally, selective logging alone has not been considered as a source of forest fragments, as it does not generally result in a dramatic loss of vegetation cover. However, depending on harvest intensity, losses of 10–60% of canopy cover from logging operations are typical and logging activities cause marked disruption and small-scale fragmentation of the forest understory, mainly by roads, skidder tracks, and patios (e.g., Pereira et al., 2002). In addition, the results of our fine-scale analyses of fragmentation indicated that canopy damage in logged areas is intense and spatially distributed throughout the logged area. This combination indicates that logged areas could, for the reasons previously highlighted, result in extensive forest fragmentation and edge-effects. The detrimental impacts of selective logging may extend many years, especially when considering that many forest structural properties, such as deep canopies, associated with wildlife habitat in intact forests, are not likely to be regained for 30–50 years or more following logging (Plumptre, 1996).

Canopy openings from logging disturbances are, however, far smaller than clearings for farms or ranches which generally lead to increased windspeeds, desiccation, and other microclimatic alterations, which in turn are key drivers of edge effects (see Laurance et al., 2002). In addition, forest edges adjoining farms or ranches are often repeatedly impacted by pasture burning, which can severely damage adjacent forests. Therefore, the penetration and magnitude of many edge effects are likely to be greater near forest to non-forest edges than near the edges of logged forest. However, large increases in fire susceptibility have been documented in forests (Cochrane et al., 2002) which result in edge-like effects following logging operations. Furthermore, the temporal trajectories of edge effects would differ, with some logged forests recovering or being managed, such as could potentially occur in over 50 million ha of National Forests (FLONAs) being established throughout the Brazilian Amazon (Veríssimo et al. 2002); while other logged areas undergo burning or subsequent deforestation.

Importantly, many species of forest-dependent fauna whose movements would be precluded by major clearings, such as cattle pastures or soy farms, probably do use logged forest (e.g. many understory birds, primates, and forest-interior insects such as certain beetles, ants, butterflies and euglossine bees; see Barlow et al., 2006, 2007 and Laurance et al., 2002), especially after a few years of forest recovery. Thus, logging alone is unlikely to isolate forest-dependent animal populations nearly to the extent of that caused by forest fragmentation from deforestation. Logging does, however, greatly facilitate hunting in some contexts (Walker, 2003), and in those cases the impacts of logging on hunted species, and the resulting fragmentation of their populations, could be far greater. Logged areas closer to settlements could result in increased hunting pressure, while those located further into forest interiors might cause a proportionally larger impact on remaining wildlife.

Edge effects can also be strongly influenced by local landscape and larger-scale climatic effects. For example, edge-related fires can penetrate up to a few kilometers into fragmented forests, and especially following logging, in more seasonal parts of the Amazon, but are less important in less-seasonal areas. The type of land-use surrounding fragments is also very important. Fragments encircled by pastures, which are often burned annually, are subjected to recurring disturbance from fires, whereas those adjoined by many crops may not experience recurring fires.

Logging edges differ from those of deforestation in several ways. First, the interface is forest-to-degraded-forest and a large variation in forest degradation exists. Second, these edges either recover through time (5–50 yrs depending on the edge effect), likely with reduced edge impact as the transition becomes less severe (Didham and Lawton, 1999), or become deforested and become hard-edges. However, logging in the Brazilian Amazon is an intense disturbance and many heavily logged areas could be considered hard-edges in some respects. It is recognized that deforestation is also dynamic, but at slower rates, with reforestation potentially occurring in many of these areas throughout the Amazon (Houghton et al., 2000), which could have a mitigating impact on the overall fragmentation caused by deforested areas. It would be of interest in future investigations of forest fragmentation to include more explicit recovery dynamics of deforested and selectively logged areas; however, the data for this analysis were not available for inclusion in the present study.

We found that rapid subdivision fragmentation occurred more from deforestation than from selective logging as log-

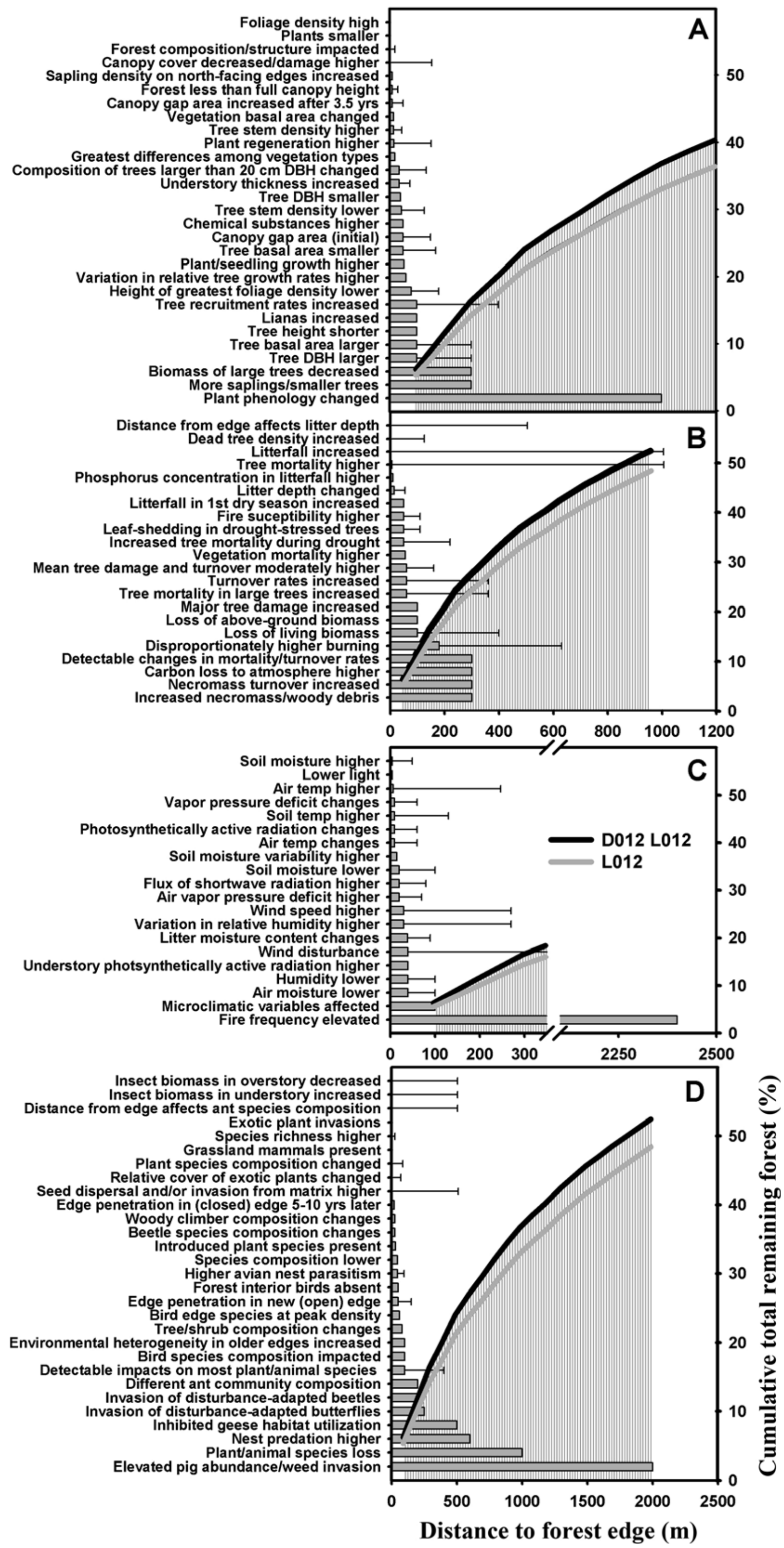

Fig. 6 – Literature review of edge effects divided into: (A) forest structure, (B) tree mortality, (C) forest microclimatic and (D) biodiversity disturbance categories. When multiple sources were identified the minimum (horizontal bar) and maximum (error bar) are provided. These effects are overlaid on area graphs to illustrate the cumulative percentage of remaining forest potentially impacted by each variable following year 2000–2002 deforestation (D012) and combined D012 and year 2000–2002 cumulative logging (CL012). The Y axis refers to the% remaining forest when logged areas are defined as either intact (D012) or degraded forest (D012–CL012). Complete references are provided online as Supplementary data.

Table 2 – Descriptive statistics of edge distance (m) into interior forest by disturbance category

Edge disturbance category	Distance (*m*)					N[a]
	Mean	Median	STD	Min	Max	
Forest structure	124	100	169	5	1000	39
Tree mortality	430	300	391	10	1000	37
Forest microclimate	191	60	386	5	2400	35
Biodiversity	261	80	385	10	2000	35
Total	245	100	358	5	2400	146

References are provided in Appendix A.
a Number of individual edge effects documented in our literature review of 62 articles.

ging extended deep into interior forests without disconnecting contiguous forest fragments. Deforestation tended to occur near previously deforested areas, and in 2002 actually reduced the percentage edge-forest as it homogenized the complex agroscape present at the exterior of larger forest fragments. Cumulative logging, however, as a result of penetrating deep into core forest areas generated 268% more edge-forest than deforestation, while generating only 64% as many new non-contiguous forest fragments. Over our study period, not only was there a dramatic increase in the number of these forest fragments, but those fragments actually became much more fragmented than expected. In addition, we find that 90% of forest fragments across our 1.1 million km^2 study area fall under Laurance's (1998) fragment area threshold of 4 km^2, -beyond which detrimental effects become more pronounced. Fortunately, these fragments encompass only ~5% of the total remaining forest area. However, this percentage will increase as larger contiguous forest areas are subdivided into smaller fragments and forest edges continue to recede (Gascon et al., 2000).

More than 53% of the ~700,000 km^2 of remaining forests in our total study area in 2002 were classified as edge-forests. Conversely, core forest area, defined as areas >2 km from the nearest forest edge, decreased from 56% to 49.7%, or by 84,303 km^2, from 1997 to 2002. New logging resulted in an annual increase of edge-forest 24 times greater than that of deforestation alone, as logging extended more deeply into the interior core of remaining intact forest areas. However, the cumulative logged area was smaller than expected from the annual mean, as new logging grew from previously logged areas and thus continually consumed previously generated edge-forest. It is important to consider that our study period was only three years, while logging has likely been occurring in the region for a much longer time. For example, if assuming that logging during the past decade has occurred at an average intensity similar to that of our study period, and that the logged areas were not subsequently deforested, then there could be 260,000 km, representing a 40% increase in total existing edge length, of undocumented soft-edges bordering ⩽10 year old logged areas.

Within our study area, Skole and Tucker (1993) calculated ~14% of remaining forests were edge-effected in 1988, using a definition of edge-forest as any forest areas within contiguous forest areas ⩽100 km^2 and closer than 1 km to a forest edge. In 2002, 14 years later, our results from deforestation alone identified ~36% of forest ⩽1 km from an edge, an increase of 1.6% per year. Total forest fragments from deforestation were 8252 and ~23,000 in 1988 and 2002, respectively. However, we acknowledge that direct comparisons of our results to those of Skole and Tucker (1993) are difficult due to differences in edge-forest definition, study area and cloud coverage, but nonetheless, we find them useful to highlight general patterns.

5. Conclusions

Fragmentation of the Amazon is rapidly creating large areas of forest susceptible to edge effects, and is reducing the area of the remaining core forest. In total, we calculated that 53% of the remaining forests in more than 1.1 million km^2 were within two km and, ~37% were within 1 km of a forest edge. Moreover, 6.4% of all remaining forests were within 100 m of a forest edge, a distance shown in our literature review to undergo extensive edge impacts. Changes in edges are not cumulative because new logging and deforestation events consume older edges. Nonetheless, large forest tracts are being divided into smaller forested sections, which become increasingly vulnerable to wildfire, human encroachment, and reductions in biomass through increased mortality following micro-meteorological changes and/or wildfire.

Deforestation served as a driver of fragmentation primarily by increasing the area of edge-forest <500 m from the nearest edge, while logging extended deeply into previously intact forest areas and created extensive edge-forest up to our two km study limit. Although logged forest habitat is preferably to deforestation when considering ecosystem function, services or biodiversity, from the perspective of edge creation, it may pose a greater threat to forest sustainability than deforestation by increasing wildfire potential and accessibility deep within previously intact core forest areas. Both deforestation and logging contributed to the sub-division of remaining forest areas into smaller non-contiguous sections, though only the impacts of deforestation were statistically significant.

Although rapid and extensive fragmentation occurred throughout our study area, the majority of remaining forests were within large contiguous forested areas, and therefore not likely to be extensively degraded by the edge effects documented in our literature review. However, the rates of forest fragmentation will likely increase in the future as the remaining forested area is reduced, and as logging continues to penetrate into these previously intact core forests. The results of this study have wide-ranging implications for carbon sequestration and release, biodiversity conservation, and social and ecological sustainability of ecosystems and human enterprises throughout the Brazilian Amazon.

Acknowledgements

We thank Rebecca Raybin for assistance with the literature review. We thank Angelica Almeyda, Lisa Curran, William Laurance, and Rob Pringle for helpful comments on the manuscript. This work was supported by NASA LBA-ECO grant NNG06GE32A and the Carnegie Institution.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.biocon.2008.04.024.

REFERENCES

Alencar, A.A., Solórzano, L.A., Nepstad, D., 2004. Modeling forest understory fires in an eastern Amazonian landscape. Ecological Applications 14, 139–149.

Asner, G.P., Keller, M., Silva, J.N.M., 2004. Spatial and temporal dynamics of forest canopy gaps following selective logging in the eastern Amazon. Global Change Biology 10, 765–783.

Asner, G.P., Knapp, D.E., Broadbent, E.N., Oliveira, P.J.C., Keller, M., Silva, J.N.M., 2005. Selective logging in the Amazon. Science 310, 480–482.

Asner, G.P., Broadbent, E.N., Oliveira, P.J.C., Keller, M., Knapp, D.E., Silva, J.N., 2006. Condition and fate of logged forests in the Brazilian Amazon. Proceedings of the National Academy of Sciences 103, 12947–12950.

Barlow, J., Peres, C.A., Henriques, L.M.P., Stouffer, P.C., Wunderle, J.M., 2006. The responses of understorey birds to forest fragmentation, logging and wildfires: An Amazonian synthesis. Biological Conservation 128, 182–192.

Barlow, J., Mestre, L.A.M., Gardner, T.A., Peres, C.A., 2007. The value of primary, secondary, and plantation forests for Amazonian birds. Biological Conservation 136, 212–231.

Benitez-Malvido, J., Martinez-Ramos, M., 2003. Impact of forest fragmentation on understory plant species richness in Amazonia. Conservation Biology 17, 389–400.

Brokaw, N.W., 1982. The definition of treefall gap and its effect on measures of forest dynamics. Biotropica 14, 158–160.

Cadenasso, M.L., Traynor, M.M., Pickett, S.T.A., 1997. Functional location of forest edges: gradients of multiple physical factors. Canadian Journal of Forest Research 27, 774–782.

Cagnolo, L., Cabido, M., Valladares, G., 2006. Plant species richness in the Chaco Serrano woodland from central Argentina: ecological traits and habitat fragmentation effects. Biological Conservation 132, 510–519.

Cochrane, M.A., 2001. Synergistic interaction between habitat fragmentation and fire in evergreen tropical forests. Conservation Biology 15, 1515–1521.

Cochrane, M.A., Laurance, W.F., 2002. Fire as a large-scale edge effect in Amazonian forests. Journal of Tropical Ecology 18, 311–325.

Cochrane, M.A., Skole, D.L., Matricardi, E.A.T., Barber, C., Chomentowski, W., 2002. Interaction and synergy between selective logging, forest fragmentation and fire disturbance in tropical forests: case study Mato Grosso, Brazil. CGCEO/RA03-02/w. Michigan State University, East Lansing, Michigan.

Cochrane, M.A., Skole, D.L., Matricardi, E.A.T., Barber, C., Chomentowski, W., 2004. Selective logging, forest fragmentation, and fire disturbance: implications of interaction and synergy. In: Zarin, D.J., Alavalapati, J.R.R., Putz, F.E., Schmink, M. (Eds.), Working Forests in the Neotropics: Conservation through Sustainable Management? Columbia University Press, New York, NY, pp. 310–324.

Cramer, J.M., Mesquita, R.C.G., Williamson, G.B., 2007. Forest fragmentation differentially affects seed dispersal of large and small-seeded tropical trees. Biological Conservation 137, 415–423.

Curran, L.M., Caniago, I., Paoli, G.D., Astianti, D., Kusneti, M., Leighton, M., Nirarita, C.E., Haeruman, H., 1999. Impact of El Nino and logging on canopy tree recruitment in Borneo. Science 286, 2184–2188.

Cushman, S.A., 2006. Effects of habitat loss and fragmentation on Amphibians: A review and prospectus. Biological Conservation 128, 231–240.

Davies-Colley, R.J., Payne, G.W., van Elswijk, M., 2000. Microclimate gradients across a forest edge. New Zealand Journal of Ecology 24, 111–121.

Defries, R., Asner, G.P., Achard, F., Justice, C., Laporte, N., Price, K., Small, C., Townshend, J., 2005. Monitoring tropical deforestation for emerging carbon markets. In: Mountinho, P., Schwartzman, S. (Eds.), Reduction of Tropical Deforestation and Climate Change Mitigation. IPAM, Washington, DC, pp. 1–27.

Didham, R.K., 1997. An overview of invertebrate responses to habitat fragmentation. In: Watt, A., Stork, N.E., Hunter, M. (Eds.), Forests and Insects. Chapman and Hall, London, pp. 201–218.

Didham, R.K., Lawton, J.H., 1999. Edge structure determines the magnitude of changes in microclimate and vegetation structure in tropical forest fragments. Biotropica 31, 17–30.

Gascon, C., Williamson, B.G., da Fonseca, G.A.B., 2000. Receding forest edges and vanishing reserves. Science 288, 1356–1358.

Hagan, J.M., Vander Haegen, M.W., McKinley, P.S., 1996. The early development of forest fragmentation effects on birds. Conservation Biology 10, 188–202.

Harper, K.A., MacDonald, S.E., Burton, P.J., Chen, J., Brosofske, K.D., Saunders, S.C., Euskirchen, E.S., Roberts, D., Jaiteh, M.S., Esseen, P.A., 2005. Edge influence on forest structure and composition in fragmented landscapes. Conservation Biology 19, 768–782.

Herrerías-Diego, Y., Quesada, M., Stoner, K.E., Lobo, J.A., Hernandez-Flores, Y., Montoya, G.S., 2008. Effects of forest fragmentation on fruit and seed predation of the tropical dry forest tree *Ceiba aesculifolia*. Biological Conservation 141, 241–248.

Hester, A.J., Hobbs, R.J., 1992. Influence of fire and soil nutrients on native and non-native annuals at remnant vegetation edges in the western Australian wheatbelt. Journal of Vegetation Science 3, 101–108.

Hobbs, R.J., 2001. Synergisms among habitat fragmentation, livestock grazing, and biotic invasions in southwestern Australia. Conservation Biology 15, 1522–1528.

Houghton, R.A., Skole, D.L., Nobre, C.A., Hackler, J.L., Lawrence, K.T., Chomentowski, W.H., 2000. Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon. Nature 403, 301–304.

INPE., 2005. Prodes: assessment of deforestation in Brazilian Amazonia. Instituto Nacional de Pesquisas Espaciais (INPE), Sao Paulo, Brazil.

Johns, A.G., Johns, B.G., 1995. Tropical forest primates and logging: long-term coexistence? Oryx 29, 205–211.

Kaimowitz, D., Angelsen, A., 1998. Economic Models of Tropical Deforestation. A Review. Center for International Forestry Research Bogor, Indonesia.

Kapos, V., 1989. Effects of isolation on the water status of forest patches in the Brazilian Amazon. Journal of Tropical Ecology 5, 173–185.
Kinnaird, M.F., Sanderson, E.W., O'Brien, T.G., Wibisono, H.T., Woolmer, G., 2003. Deforestation trends in a tropical landscape and implications for endangered large mammals. Conservation Biology 17, 245–257.
Laurance, W.F., 2000. Do edge effects occur over large spatial scales? Trends in Ecology and Evolution 15, 134–135.
Laurance, W.F., Williamson, G.B., 2001. Positive feedbacks among forest fragmentation, drought, and climate change in the Amazon. Conservation Biology 15, 1529–1535.
Laurance, W.F., Laurance, S.G., Ferreira, L.V., Rankin-De Merona, J.M., Gascon, C., Lovejoy, T.E., 1997. Biomass collapse in Amazonian forest fragments. Science 278, 1117–1118.
Laurance, W.F., Ferreira, L.V., Rankin-De Merona, J.M., Laurance, S.G., 1998. Rainforest fragmentation and the dynamics of Amazonian tree communities. Ecology 79, 2032–2040.
Laurance, W.F., Delamonica, P., Laurance, S.G., Vasconcelos, H.L., Lovejoy, T.E., 2000. Rainforest fragmentation kills big trees. Nature, 404.
Laurance, W.F., Lovejoy, T.E., Vasconcelos, H.L., Bruna, E.M., Didham, R.K., Stouffer, P.C., Gascon, C., Bierregaard, R.O., Laurance, S.G., Sampaio, E., 2002. Ecosystem decay of Amazonian forest fragments: a 22-year investigation. Conservation Biology 16, 605–618.
Laurance, W.F., Nascimento, H.E.M., Laurance, S.G., Andrade, A.C., Fearnside, P.M., Ribeiro, J.E.L., Capretz, R.L., 2006. Rain forest fragmentation and the proliferation of successional trees. Ecology 87, 469–482.
Lawton, J.H., Bigness, D.E., Bolton, B., Bloemers, G.F., Eggleton, P., Hammond, P.M., Hodda, M., Holt, R.D., Larsen, T.B., Mawdsley, N.A., Stork, N.E., Srivastava, D.S., Watt, A.D., 1998. Biodiversity inventories, indicator taxa and effects of habitat modification in tropical forest. Nature 391, 72–76.
Lovejoy, T.E., Bierregaard Jr., R.O., Rylands, A.B., Malcom, J.R., Quintela, C.E., Harper, L.H., Brown Jr., K.S., Powell, A.H., Powell, G.V.H., Schubart, H.O.R., Hays, M.B., 1986. Edge and other effects of isolation on Amazon forest fragments. In: Soulé, M.E. (Ed.), Conservation Biology: the Science of Scarcity and Diversity. Sinauer, Sunderland, Massachusetts, pp. 257–285.
Malcolm, J.R., 1997. Insect biomass in Amazonian forest fragments. In: Stork, N.E., Adis, J., Didham, R.K. (Eds.), Canopy Arthropods. Chapman and Hall, London, pp. 510–533.
Mason, D.J., Thiolay, J.M., 2001. Tropical forestry and the conservation of neotropical birds. In: Fimbel, R.A., Grajal, A., Robinson, J.G. (Eds.), The Cutting Edge: Conserving Wildlife in Logged Tropical Forests. Columbia University Press, New York, NY, pp. 167–191.
Matlack, G.R., 1993. Microenvironment variation within and among forest edge sites in the eastern United States. Biological Conservation 66, 185–194.
Mesquita, R.C.G., Delamonica, P., Laurance, W.F., 1999. Effect of surrounding vegetation on edge-related tree mortality in Amazonian forest fragments. Biological Conservation 91, 129–134.
Mulkey, S.S., Pearcy, R.W., 1992. Interactions between acclimation and photoinhibitation of photosynthesis of a tropical forest understory herb, *Alocasia macrorrhiza*, during simulate canopy gap formation. Functional Ecology 6, 719–729.
Murcia, C., 1995. Edge effects in fragmented forests: implications for conservation. Trends in Ecology and Evolution 10, 58–62.
Nascimento, H.E.M., Laurance, W.F., 2004. Biomass dynamics in Amazonian forest fragments. Ecological Applications 14, S127–S138.
Nepstad, D.C., Brown, F.I., Luz, L., Alechandre, A., Viana, V., Schwartzman, S., 1992. Biotic impoverishment of Amazonian forests by rubber tappers, loggers, and cattle ranchers. Advances in Economic Botany 9, 1–14.
Nepstad, D., Verissimo, A., Alencar, A., Nobre, C., Eirivelthon, L., Lefebvre, P., Schlesinger, P., Potter, C., Moutinho, P., Mendoza, E., Cochrane, M., Brooks, V., 1999. Large-scale impoverishment of Amazonian forests by logging and fire. Nature 398, 505–508.
Nichols, E., Larsen, T., Spector, S., Davis, A.L., Escobar, F., Favila, M., Vulinec, K.The Scarabaeinae Research Network, 2007. Global dung beetle response to tropical forest modification and fragmentation: a quantitative literature review and meta-analysis. Biological Conservation 137, 1–19.
Pereira Jr., R., Zweede, J., Asner, G.P., Keller, M., 2002. Forest canopy damage and recovery in reduced-impact and conventional selective logging in eastern Para, Brazil. Forest Ecology and Management 168, 77–89.
Peres, C.A., 2001. Synergistic effects of subsistence hunting and habitat fragmentation on Amazonian forest vertebrates. Conservation Biology 15, 1490–1505.
Peters, H.A., 2000. *Clidemia hirta* invasion at the Pasoh forest reserve: an unexpected plant invasion in an undisturbed tropical forest. Biotropica 33, 60–68.
Plumptre, A.J., 1996. Changes following 60 years of selective timber harvesting in the Budongo forest reserve, Uganda. Forest Ecology and Management 113, 201–213.
Pringle, C.M., Benstead, J.P., 2001. The effects of logging on tropical river ecosystems. In: Fimbel, R.A., Grajal, A., Robinson, J.G. (Eds.), The Cutting Edge: Conserving Wildlife in Logged Tropical forests. Columbia University Press, New York, NY, pp. 305–325.
Putz, F.E., Blate, G.M., Redford, K.H., Fimbel, R., Robinson, J., 2001a. Tropical forest management and conservation of biodiversity: an overview. Conservation Biology 15, 7–20.
Putz, F.E., Sirot, L.K., Pinard, M.A., 2001b. Tropical forest management and wildlife: silvicultural effects on forest structure, fruit production, and locomotion of arboreal animals. In: Fimbel, R.A., Grajal, A., Robinson, J.G. (Eds.), The Cutting Edge: Conserving Wildlife in Logged Tropical Forests. Columbia University Press, New York, NY, pp. 11–35.
Ranta, P., Blom, T., Niemela, J., Joensuu, E., Siitonen, M., 1998. The fragmented Atlantic rain forest of Brazil: size, shape and distribution of forest fragments. Biodiversity and Conservation 7, 385–403.
Rodríguez-Cabal, M., Aizen, M.A., Novaro, A.J., 2007. Habitat fragmentation disrupts a plant-disperser mutualism in the temperate forest of South America. Biological Conservation 139, 195–202.
Saunders, D.A., Hobbs, R.J., Margules, C.R., 1991. Biological consequences of ecosystem fragmentation: a review. Conservation Biology 5, 18–32.
Schlaepfer, M.A., Gavin, T.A., 2001. Edge effects on lizards and frogs in tropical forest fragments. Conservation Biology 15, 1079–1090.
Sizer, N.C., Tanner, E.V.J., Kossman Ferraz, I.D., 2000. Edge effects on litterfall mass and nutrient concentrations in forest fragments in central Amazonia. Journal of Tropical Ecology 16, 853–863.
Skole, D., Tucker, C., 1993. Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 to 1988. Science 260, 1905–1911.
Soriano, P.J., Ochoa, J.G., 2001. The consequences of timber exploitation for bat communities in tropical America. In: Fimbel, R.A., Grajal, A., Robinson, J.G. (Eds.), The Cutting Edge: Conserving Wildlife in Logged Tropical Forests. Columbia University Press, New York, NY, pp. 153–166.
Tabanez, A.A.J., Viana, V.M., 2000. Patch structure within Brazilian Atlantic forest fragments and implications for conservation. Biotropica 32, 925–933.

Uhl, C., Buschbacher, R.A., 1985. A disturbing synergism between cattle ranch burning practices and selective tree harvesting in the eastern Amazon. Biotropica 32, 925–933.

Uhl, C., Verissimo, A., Mattos, M., Brandino, Z., Vieira, I.C., 1991. Social, economic, and ecological consequences of selective logging in an Amazon frontier: the case of Tailandia. Forest Ecology and Management 46, 243–273.

Veríssimo, A., Barreto, P., Mattos, M., 1992. Logging impacts and prospects for sustainable forest management in an old Amazonian frontier: the case of Paragominas. Forest Ecology and Management 55, 169–199.

Veríssimo, A., Cochrane, M., Souza Jr., C., 2002. National forests in the Amazon. Science 297, 1478.

Walker, W., 2003. Mapping process to pattern in landscape change of the Amazonian frontier. Annuals of the Association of American Geographers 93, 376–398.

Williams-Linera, G., Dominguez-Gastelu, V., Garcia-Zurita, M.E., 1998. Microenvironment and floristics of different edges in a fragmented tropical rainforest. Conservation Biology 12, 1091–1102.

Young, A., Mitchell, N., 1994. Microclimate and vegetation edge effects in a fragmented podocarp-broadleaf forest in New Zealand. Biological Conservation 67, 63–72.